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Key Points:
- Satellite-derived suspended sediment concentration (SSC) shows rivers recovery to pre-reservoir SSC downstream of 71% of dams in the US
- The length of river required to longitudinally recover SSC downstream of dams is most strongly associated with reservoir and river size
- Multidecadal satellite SSC observations provide a new metric for assessing the long-term mean downstream response to dams

Correspondence to:
R. Prajapati,
livaraja08@gmail.com

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Author Contributions:
Conceptualization: R. Prajapati, J. Gardner, R. Talchabhadel
Formal analysis: R. Prajapati, J. Gardner, R. Talchabhadel
Funding acquisition: R. Prajapati, J. Gardner
Investigation: R. Prajapati, R. Talchabhadel
Methodology: R. Prajapati, J. Gardner, R. Talchabhadel
Project administration: R. Prajapati, J. Gardner
Supervision: R. Prajapati, J. Gardner, T. Pavelsky, R. Talchabhadel
Visualization: R. Prajapati, R. Talchabhadel
Writing – original draft: R. Prajapati, R. Talchabhadel
Writing – review & editing: R. Prajapati, J. Gardner, T. Pavelsky, R. Talchabhadel

Longitudinal Recovery of Suspended Sediment Downstream of Large Dams in the US

R. Prajapati[1], J. Gardner[1], T. Pavelsky[2], and R. Talchabhadel[3]

[1]Department of Geology and Environmental Science, University of Pittsburgh, Pittsburgh, PA, USA, [2]Department of Earth, Marine and Environmental Sciences, University of North Carolina, Chapel Hill, NC, USA, [3]Department of Civil and Environmental Engineering, Jackson State University, Jackson, MS, USA

Abstract Dams disrupt the natural flow of water and sediment along rivers. Reservoirs trap a significant amount of sediment, which substantially alters downstream hydrology, channel morphology, and sediment transport capacity. The longitudinal recovery of suspended sediment concentration (SSC) along rivers is potentially a new metric for estimating downstream responses to dams over space, rather than time, but is rarely quantified due to the lack of spatial SSC data. Satellites can estimate SSC along rivers where no field data exist and provide a high enough spatial resolution for assessing downstream recovery at the scale of tens to hundreds of kilometers. Here, we use a recently published database of spatially explicit SSC observations derived from Landsat to quantify if a river recovers or not, the SSC recovery percentage, and SSC recovery length downstream of large dams across the Contiguous United States (CONUS). Rivers recover SSC downstream of most dams (71%). The chance of a river recovering and the length of river required to recover SSC is associated primarily with the size of the reservoir (mean storage, km^3) and the size of the river (mean discharge, m^3/s). Rivers were more likely to recover SSC downstream of run-of-river, navigation dams compared to large storage or hydropower dams. Our results suggest that rivers typically recover suspended sediment downstream of dams, influenced by factors like dam storage, purpose, and river channel characteristics.

1. Introduction

A fundamental function of rivers is to move sediment downstream (Phillips, 2010). A river's ability to move sediment is important for maintaining dynamic stability and supplying coasts with sediment (Nienhuis et al., 2020; Syvitski et al., 2005). Reductions in riverine sediment loads can lead to "hungry waters" eroding riverbeds and banks (Kondolf, 1997), while increased sediment loads lead to deposition, potentially changing channel form and raising riverbed elevations, which can increase risk of flooding. Human activities, such as land use change and direct river management alter sediment loads (Dethier et al., 2022; Syvitski et al., 2005), but dams are the most significant disruptor of riverine sediment transport (Best, 2019). Dams and their reservoirs intercept and trap over 25% of the global sediment load (Vörösmarty et al., 1997, 2003), leading to substantial changes in downstream hydrology, channel morphology, and sediment transport capacity (Graf, 2006; Milliman & Farnsworth, 2013). The natural flow of most large rivers is now influenced by dams, with 63% of the world's longest rivers (>1,000 km) no longer free-flowing, accounting for 41% of worldwide river volume (Grill et al., 2019). Furthermore, if proposed and ongoing hydropower projects move forward, natural flows will be altered for 93% of river volume worldwide by 2030 (Kotzé, 2022). Given the global significance of dams in riverine sediment transport, we need a better understanding of how rivers adjust and recover downstream of dams using metrics that can be applied globally including data sparse regions.

Work on the downstream impacts of dams has largely focused on pre- and post-dam construction over time (Petts, 1979), while we have fewer observations and understanding of how rivers change over space above reservoirs and below their dams. Past work of how rivers respond to dams over time using both upstream and downstream measurements focused on changes in channel form and sediment properties, such as bank erosion rates, textural modification of river bed sediments, and changes in channel width and depth (Brandt, 2000a; Grant et al., 2003; Kondolf, 1997; Williams & Wolman, 1984). Dams reduce riverine sediment loads before and after dam construction with sediment trapping efficiencies of large reservoirs often close to 99% (Williams & Wolman, 1984) but ranges from 10% to 90% for smaller dams (Brune, 1953; Moragoda et al., 2023). One of the few studies on downstream SSC changes over space compared sediment loads before dam construction to 2–3 points downstream of a dam after its construction for a few Western US dams. They found sediment loads often did not recover to pre-construction loads or required 200–1,300 km to recover (Williams & Wolman, 1984). SSC or discharge are rarely available before and after dam construction, but we can leverage satellite records to study rivers' downstream response to dams over space in the decades following dam construction.

Satellites, specifically Landsat, has proven capable of estimating SSC in rivers over the decades (Beveridge et al., 2020; Dethier et al., 2022; Gardner et al., 2023a, 2023b; Gholizadeh et al., 2016; Pavelsky & Smith, 2009; Ritchie et al., 1987; Yepez et al., 2018; Zhang et al., 2014). Spatial SSC observations along rivers can be used to develop new metrics for downstream response to dams. Here, we focus on longitudinal SSC percent recovery and recovery length. We define longitudinal SSC percent recovery by comparing SSC downstream of dams to SSC upstream of reservoirs and longitudinal SSC recovery length as the distance from the dam to where recovery is ~100%. We focus on SSC because suspended sediment dominates the total sediment load in large river systems (Cohen et al., 2021; Li et al., 2022; Sadeghi & Singh, 2017; Walling & Webb, 1986) and can be estimated with satellites.

We used a new SSC database derived from Landsat 5, 7, and 8 that is linked to US river hydrography with topology, RivSed (Gardner et al., 2023a, 2023b), to quantify longitudinal SSC recovery downstream of large dams across large US rivers. SSC, instead of suspended sediment load, was the focus for quantifying percent recovery and recovery length since our goal was to use a spatial metric that can be applied in any large river in the US using RivSed, and globally with ongoing development of this database. River discharge is not currently available as spatial data. Further, discharge tends to increase downstream, and therefore sediment load will obscure signals of sediment recovery due to changes in sediment concentration as discharge dominates calculations of load (Hoffman et al., 2023). Here, we offer proof of concept of a new, spatially explicit approach to quantify longitudinal SSC recovery over space downstream of dams using long-term mean SSC observations in the period after dam construction

Our questions are:

(1) How common is longitudinal SSC recovery downstream of large dams?
(2) What is the downstream length required for longitudinal SSC recovery?
(3) What are the factors that influence longitudinal SSC recovery and recovery length?

2. Data and Methods

2.1. Suspended Sediment Concentration (SSC)

To best determine if rivers recover SSC downstream of dams over space, we need a time-integrated signal that is spatially explicit along rivers, therefore we focus on long-term mean SSC. The database RivSed uses Landsat 5, 7, and 8 images and a single machine learning algorithm trained on >28,000 coincident field and satellite observations (Ross et al., 2019) to estimate SSC at reach scales represented by National Hydrography Data set Plus Version 2 (NHDPlusV2) centerlines (Moore & Dewald, 2016a, 2016b). Currently, RivSed is a cohesive 34-year record (1984–2018) at each reach (~2 km river lengths on average) with 15.9 million SSC observations in total which we collapsed into long-term mean SSC at each reach. The RivSed algorithm has a mean absolute error (MAE) of 12 mg/l, Root Mean Square Error of 29 mg/l and a prediction range of 0.6–2,228 mg/L, but note MAE and relative bias are the preferred metrics for validation of remote sensing of water quality, particularly parameters that can span several orders of magnitude such as SSC (Seegers et al., 2018). There are many limitations to RivSed and remote sensing of SSC in general (see Gardner et al., 2023a, 2023b for further discussion), such as Landsat can only observe SSC near the surface of the water column. Our questions do not require depth-integrated SSC as we are not quantifying sediment flux nor volumes of eroded material. Here we are only comparing longitudinal gradients using long-term mean SSC; therefore, limitations in accuracy and bias of remotely sensed SSC are overcome by quantifying relative spatial change in SSC using millions of observations (Narayanan et al., 2023).

2.2. Dam Database

Our primary source of information on dams was the National Anthropogenic Barrier Dataset (NABD; Ostroff et al., 2013). NABD spatially links the point data set of the 2009 National Inventory of Dams (NID) from the U.S. Army Corps of Engineers to NHDPlusV2. NABD was merged with NHDPlusV2 and RivSed. However, it is important to note that this data set comprises various dam types, such as dikes, saddle dams, side dams, etc.

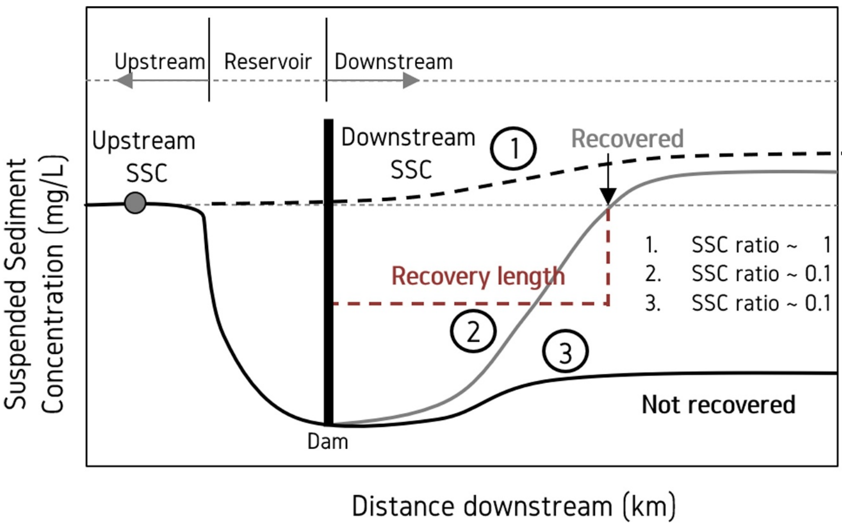

Figure 1. Schematic diagram for suspended sediment concentration (SSC) recovery. The SSC ratio is the ratio of SSC of the river segment just downstream of the dam to reference SSC upstream of the reservoir. SSC ratio is ∼1 for case 1, as SSC downstream of dam and SSC upstream of the reservoir are similar whereas SSC ratio for cases 2 and 3 are less than 1 as downstream SSC is smaller than upstream SSC.

(Renwick et al., 2005). Thus, we developed specific criteria to filter the primary dam, which releases water and sediment from its reservoir to the downstream river (Moragoda et al., 2023). Dams were selected for further analysis based on the following criteria: only large dams were selected, which we define as dams with height greater than 15 m, dam storage greater than 12 km^3, and river width greater than 60 m so that it can be captured by Landsat (spatial resolution of 30 m). Among 231 dams that fit the criteria mentioned above, only 109 dams were chosen for further analysis as the other dams had insufficient Landsat-derived SSC data points. Dams with fewer than 15 downstream SSC observations were omitted from the analysis to ensure enough spatial coverage to observe longitudinal SSC patterns and its potential recovery. The average age of the analyzed dams is 70 years and only two started operation shortly after 1984, therefore the long-term mean SSC from 1985 to 2018 provides a river SSC "climatology" after dams have been in place and rivers have likely adjusted to their presence.

2.3. SSC Recovery Percentage and Recovery Length

In order to determine longitudinal SSC recovery downstream of the dam, the SSC values for each river reach along the free flow length downstream of the dam was compared to an upstream reference SSC. Free flow length refers to the maximum length of the unobstructed flow of a river downstream of a dam before the river meets a barrier (i.e., a reservoir of the next large downstream dam which meets the criteria mentioned in Section 2.2, a larger river with higher mean discharge compared to the reference river, or a terminal outlet at the ocean or international border). Reference SSC refers to the average SSC value of 10 river reaches just upstream of the reservoir to reduce bias from any individual reach that may not be representative of the river upstream of the reservoir due to static river and reservoir reach designation from NHDPlusV2. Longitudinal SSC recovery percentages of all reaches downstream of dams were calculated with respect to upstream reference SSC. Longitudinal SSC recovery refers to 100% SSC recovery and its corresponding length from the dam to the point where 100% recovery is achieved is termed as recovery length (Figure 1). We also calculated the maximum longitudinal recovery percentage defined as the highest percentage of recovered SSC that is reached along the free-flow length downstream of the dam.

2.4. Factors Affecting SSC Recovery

Dam, channel, and watershed characteristics were collected from different data sources to assess factors related to the SSC recovery downstream of dams. Dam characteristics, such as dam height (m), dam storage (cubic km), and dam purpose were obtained from NABD and NID. The change in SSC directly linked to the reservoir was calculated using the SSC ratio. The SSC ratio is the ratio of SSC of the river segment just downstream of the dam compared to the reference SSC upstream of the reservoir. In addition, we obtained several relevant channel characteristics. Long-term average discharges of river segments from NHDPlusV2, and free flow length was calculated from adding up NHDPlusV2 reach lengths. Finally, we obtained relevant watershed characteristics. Long-term average rainfall, runoff, and land cover metrics over local catchments directly draining all river segments downstream of dams, but not upstream of the dams, were obtained from the StreamCat data set (Hill et al., 2016) using land cover metrics from 2001 as a representative year in the middle of the 1985–2018 period represented in long-term mean SSC. StreamCat catchment level land cover categories were aggregated into six major categories (Water, Built, Barren, Natural, Agriculture, and Wetland). Land cover data was computed by averaging the percentage of a specific land cover category across all catchments downstream of the dam excluding any upstream contribution. Tributary density is determined by calculating the ratio of the number of tributaries flowing into the mainstem river downstream of a dam over the free-flow length. Meanwhile, the tributary discharge ratio is computed as the ratio of the cumulative discharge contributed by all these same tributaries to the total discharge of the river segment located farthest downstream within its free-flow length.

The partial correlations were computed by considering the relation between the dependent variable and an independent variable, while accounting for the influences of all other independent variables, thus isolating the specific relationship of interest. Spearman's r correlation coefficient (Lee Rodgers & Nicewander, 1988) was used to describe the strength of linear relationships between SSC recovery lengths and different dam, channel and watershed characteristics as a proof of concept that SSC recovery and recovery lengths is associated with channel, dam, and/or watershed properties. The significance of correlations was tested with two-tailed p-value hypothesis tests using an alpha level of 0.05. We used the Kolmogorov-Smirnov test to identify whether the same factors were associated with rivers that fully recovered SSC versus those that did not recover.

3. Results and Discussion

3.1. Suspended Sediment Recovery

Examining the full data set of dams shows that maximum longitudinal SSC recovery percentage varied widely, from 21% to over 750%, with an average of 140%. The least recovered dam was Falcon dam (21%) on the Rio Grande, whereas the most recovered dam was Whitney Lake dam (768%) on the Brazos River (Texas). Among 109 dams, 71% (77 dams) fully recovered and 95% of dams (104 dams) had at least 50% recovery of SSC downstream.

Recovery lengths for fully recovered rivers range from 0 km to around 390 km, with an average length of 54 km (Figure 2). The Amistad dam on the Rio Grande had the longest recovery length (390 km). The result shows that more than two-thirds of fully recovered rivers had a recovery length less than 50 km, and only 15% of fully recovered rivers had a recovery length greater than 100 km (Figure 2). Most river segments on the Ohio and Mississippi Rivers recovered quickly, with full recovery lengths less than 5 km. More than 50% of dams in the Pacific Northwest and South Atlantic regions fully recovered SSC within 20 km downstream. Almost all dams in the Missouri, Arkansas, Texas, Rio Grande and Northeast regions had full recovery lengths greater than 50 km. Rivers need space in between dams, on average 54 km, to recover SSC.

3.2. Factors Affecting SSC Recovery Length

We found SSC recovery length is influenced more by channel properties and dam characteristics compared to catchment scale properties. Using partial correlation analysis of recovery length versus five independent variables (dam height, dam storage, long-term mean river discharge, free flow length, and tributary discharge ratio) showed dam storage and river discharge were significantly correlated with SSC recovery length (Figure 3). However, dam height, free-flow length, and tributary density were not significant when accounting for the effect of all five independent variables simultaneously. This suggests as reservoir size increases and river size decreases, it is more likely to require a longer distance downstream of dams for SSC to return to pre-reservoir concentrations.

Many other factors are likely related to SSC recovery length but become statistically insignificant in partial correlations analysis given the inherent relationship among many hydrologic variables. Therefore, we also conducted simple correlations between SSC recovery length and influencing factors to discuss the complex interrelationships among factors and SSC recovery. We focus interpretation on the direction of the relationship, positively or negatively correlated, to contextualize our results within existing knowledge of downstream

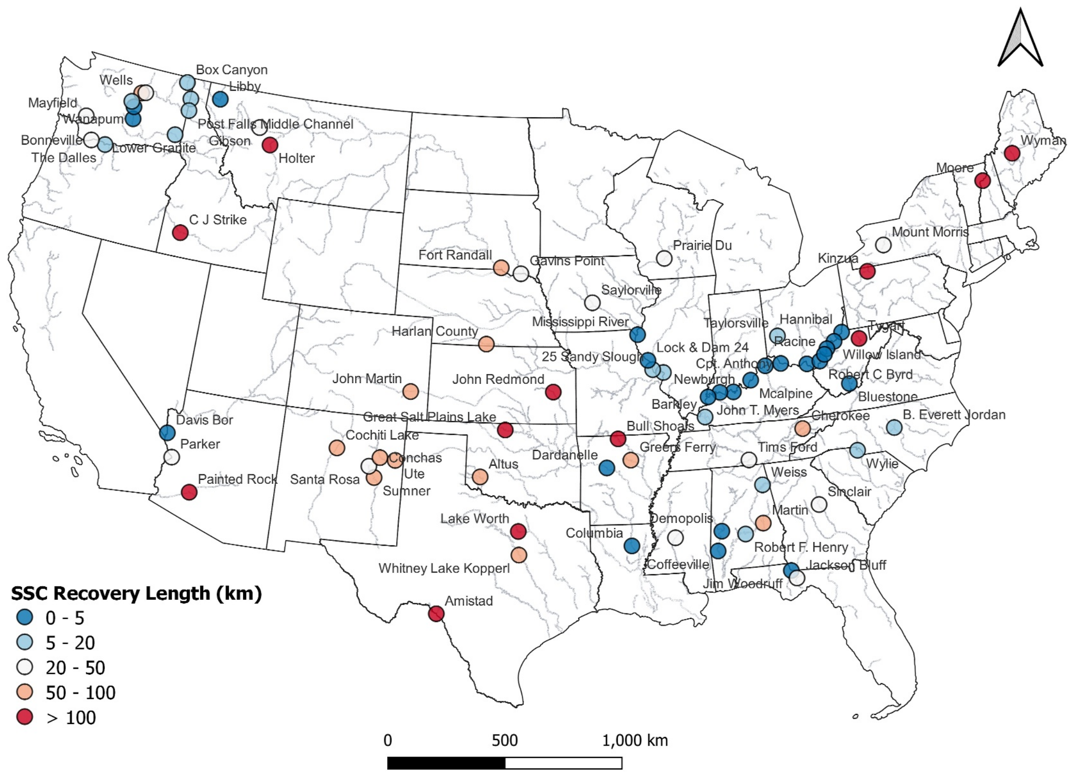

Figure 2. Map of dam locations and suspended sediment concentration recovery lengths for dams with 100% recovery. Blue circles are dams with the shortest recovery lengths, while dams with the highest recovery lengths are shown in red circles.

response to dams. This provides further proof of concept that our estimates of SSC recovery percent and recovery length from satellites have hydrogeomorphic meaning and provide a new metric to assess downstream SSC recovery over space.

Dam height and reservoir storage were positively correlated with SSC recovery length ($r = 0.26$ and 0.34, respectively). Large reservoirs usually trap a significant amount of sediment, releasing only a fraction of sediment to the downstream reaches (Brandt, 2000b). Glen Canyon, one of the tallest dams in the US, never fully recovered SSC downstream, and it took more than 430 km to recover 75% of upstream SSC. Similarly, rivers impacted by other large dams such as Yellow Tail, Summersville, Hells Canyon, and Wolf Creek recovered just a fraction of upstream SSC (Table 1).

Dam purpose is also likely related to SSC recovery length, but dam purpose is often linked to reservoir storage or dam height as well. Dams built for navigation purposes are typically run-of-river dams (Remo et al., 2016) that can pass fine sediment and have relatively lower dam height and storage compared to hydropower and flood control dams (Figure 4). Out of 109 dams, 38 dams listed navigation as one dam purpose, and the average height of these navigation dams was 36 ± 19 m, lower than non-navigation dams (53 ± 33 m). The average recovery length for non-navigation dams (75 ± 88 km) was more than three times the length of navigation dams (21 ± 61 km). To demonstrate the impact of dams and their purpose, we show a case study of the Missouri and Ohio Rivers (Figure 5). In the Missouri River, reservoirs behind large dams caused large decreases in SSC resulting in smaller SSC ratios. The SSC value just downstream of the dam was a small fraction of the reference SSC, and long river lengths were required to recover SSC. Conversely, the run-of-river dams along the Ohio River do not have significant impoundments and likely trap little sediment considering the significantly higher SSC ratios compared to large storage reservoirs (Figure 5).

Another factor that influences the SSC recovery downstream of dams is the length of uninterrupted river flow or free flow length. Free flow length had a statistically significant positive correlation recovery length ($r = 0.68$) (Figure 6). Rivers gradually collect sediment from different sources moving downstream such as bed scouring, river bank erosion, sediment from smaller tributaries, and soil erosion from adjacent catchments. The longer the

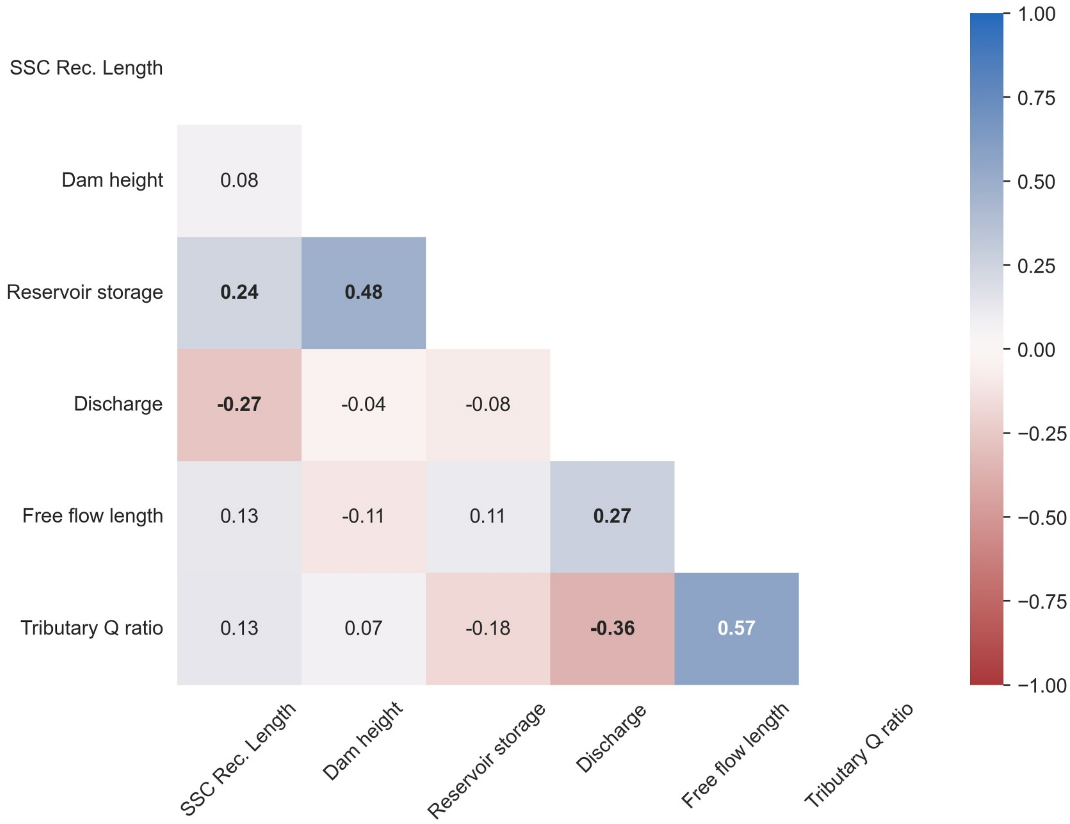

Figure 3. Partial correlation of suspended sediment concentration recovery length and different variables.

free flow length, the higher the chance of SSC recovery downstream. Gavins Point dam (Missouri River), with a free flow length of 1,280 km recovered more than 600% of SSC 1,060 km downstream. The shortest free flow length of 44 km was observed in Hartwell dam (Savannah River) which recovered 68% of SSC. Among 38 navigation dams, only 8 dams did not fully recover SSC, 2 of which had a recovery percentage greater than 98%. The SSC recovery of the remaining 6 navigation dams was limited mainly due to insufficient free flow lengths. Since free flow lengths were defined by river reaches without confluences with rivers larger than itself, our analysis suggests in- and near-channel sediment sources and erosion may be an important sediment source to downstream SSC recovery.

We found the weakest simple correlations between catchment scale factors and SSC recovery length, but the direction of the relationship agrees with previous studies. We found tributary density had a statistically significant negative correlation ($r = -0.31$) with SSC recovery length (Figure 6). Tributaries have potential to disrupt the

Table 1
Examples of Suspended Sediment Concentration Recovery Percentage and Recovery Length From Select Large Dams (NR = Not Recovered) With Heights Greater Than 75 m

Dams (River)	Dam height (m)	Dam storage (km^3)	Recovery percentage (corresponding length in km)	Recovery length (km)
Glen Canyon (Colorado River)	216	36.8	75% (431)	NR
Yellow Tail (Bighorn River)	160	1.76	36% (117)	NR
Summersville (Gauley River)	119	0.51	97% (17)	NR
Hells Canyon (Snake River)	100	0.230	58% (222)	NR
Wolf Creek (Cumberland River)	79	7.51	34% (116)	NR
Amistad (Rio Grande River)	87	6.33	100% (390)	390
Bull Shoals (White River)	86	6.67	100% (249)	249

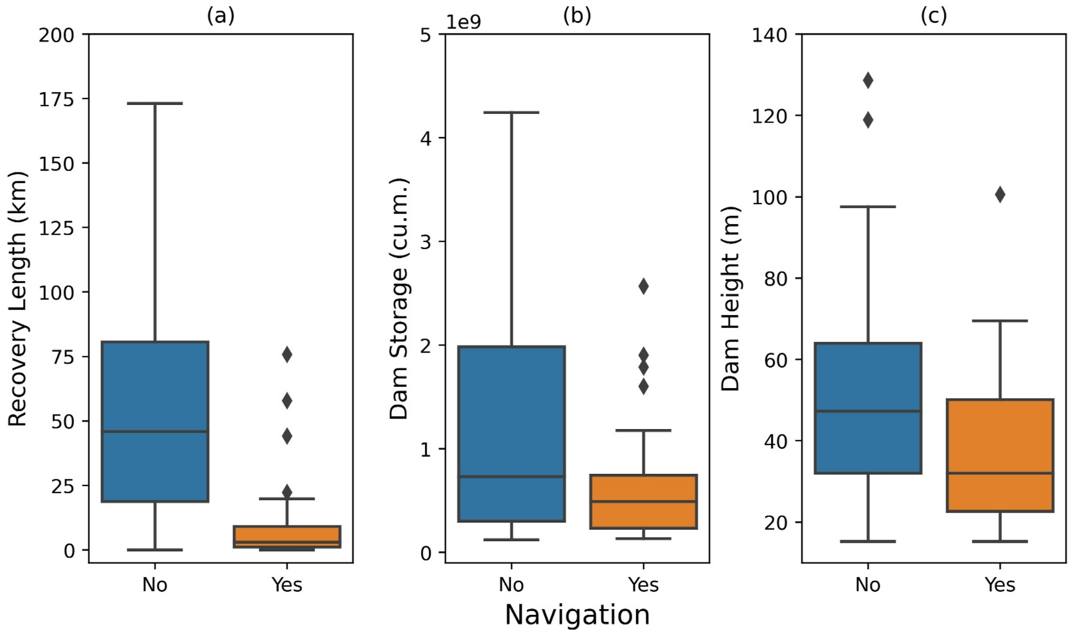

Figure 4. Boxplots showing the distribution of (a) recovery length, (b) dam storage, and (c) dam height for navigation (orange box) and non-navigation dams (blue box).

longitudinal patterns of SSC of the main river by changing both discharge and SSC (Ghosh, 2022). Higher tributary density often leads to an increased SSC in the main river channel as more tributaries mean more sources of sediment (Rice & Church, 2001). Conversely, the tributary discharge ratio, which is the ratio of the cumulative discharge contributed by all tributaries to the total discharge of the river segment located farthest downstream within its free-flow length, showed a statistically significant positive correlation (r = 0.40) with SSC recovery length. This implies that higher tributary discharge is associated with reduced SSC in the main channel, which could be attributed to the dilution effect. SSC recovery length had very weak positive correlations with natural (r = 0.20), and agricultural land cover percent (r = −0.17) (Figure 6). Agricultural and natural land uses were the dominant land use categories in the catchments represented by river segments downstream of major dams. More than 90% of dams had a dominant land cover type of "natural" in their local catchments, and only 8% of dams were dominated by agricultural land cover, therefore we may not have a representative sample of different land covers. The direction of the correlations are logical however, as soil erosion rates are typically highest on agricultural land and lowest on natural land (Nigatu, 2014; Tadesse et al., 2017). Our findings are consistent with the observations that the impacts of dams on hydrology, geomorphology, and ecology occur largely directly up and downstream of dams and diminish moving downstream (Jacobson & Galat, 2008; Pyron & Neumann, 2008).

3.3. Factors Affecting SSC Recovery

In addition to factors affecting recovery length, we also tested if the same factors were associated with rivers that fully recovered SSC versus those that did not recover using the Kolmogorov-Smirnov test. Discharge, dam storage, SSC ratio and free flow length were associated with significant differences in recovered and non-recovered rivers (Figure 9), whereas rainfall, runoff, dam height, and natural and agricultural land covers were not associated with significant differences between the two groups. In general, recovered rivers had higher river discharge compared to non-recovered rivers. The average river discharge for non-recovered rivers was 261 m^3/s, ranging from 13 to 1,524 m^3/s, whereas the river discharges for recovered rivers varied widely from 1.27 to 5,502 m^3/s with an average value of 1,102 m^3/s (Figure 7a).

Rivers with discharge greater than 500 m^3/s typically recovered SSC downstream (Figure 8). The average reservoir storage for recovered rivers was 1.10 km^3. Compared to 2.59 km^3 for non-recovered rivers. In the case of the SSC ratio, recovered rivers had higher ratios (average = 0.69 ± 0.33) than non-recovered rivers (average = 0.36 ± 0.33). Larger dams with larger reservoir volumes can trap more sediment resulting in lower

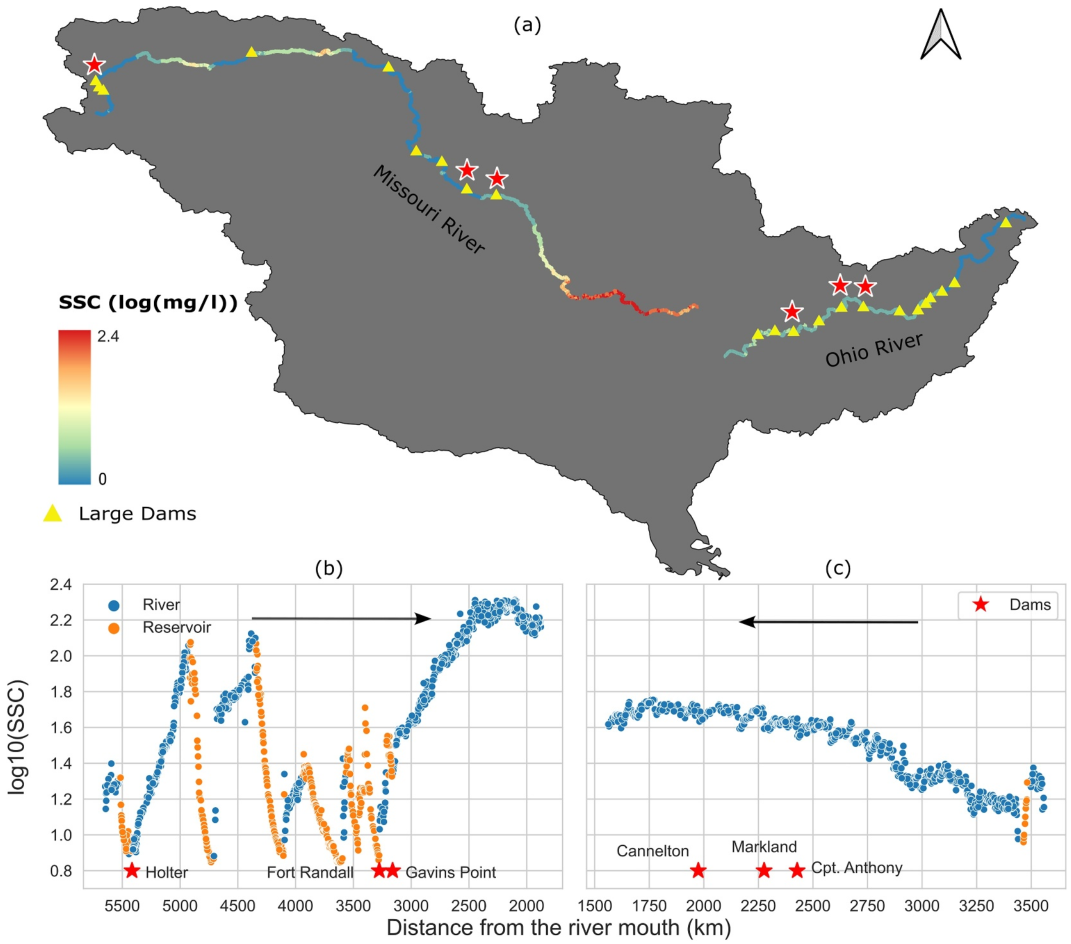

Figure 5. (a) Map of Mississippi river basin showing the longitudinal variation of the suspended sediment concentration (SSC) (log 10 of SSC) along the mainstem of Missouri River and Ohio River. Large dams are shown as yellow markers. Graph showing the longitudinal variation of the SSC along the mainstem of (b) Missouri River and (c) Ohio River. For both graphs, vertical axes represent the logarithmic transformation of SSC (mg/l) and horizontal axes are the distance from the river mouth (km). Blue dots represent free river reaches (River) and the orange dot represents impounded river reaches (Reservoir). Select dams are shown as red stars. The black horizontal arrows point to the flow direction of the rivers.

SSC ratios; therefore, recovered rivers had lower reservoir storage and higher SSC ratios. The threshold SSC ratio for SSC recovery was 0.60 (Figure 8). The ability of rivers to recover SSC downstream of dams may also depend on the free flow length. The average free flow length for non-recovered rivers was 196 km, ranging from 44 to 1,222 km, while the free flow length for recovered rivers varied from 47 to 1,875 km with an average value of 251 km. Rivers that longitudinally recover SSC downstream of US dams, are likely to be larger rivers, with higher discharge, sediment carrying capacity, and have longer unobstructed free flowing rivers downstream to collect more sediment.

4. Conclusions

Our study shows that rivers, surprisingly, recover surface SSC downstream of most dams (71%) analyzed here, but the likelihood of recovery and recovery length is dependent on dam storage, dam purpose and river characteristics. Rivers showed a greater tendency for SSC recovery downstream of run-of-river or navigation dams compared to large storage or hydropower dams. While dams cause an irreversible reduction in SSC or sediment load over time (Kondolf, 1997) until the dam is removed, dams typically do not cause irreversible reductions over space given that most rivers recover SSC (71%) at some point downstream. It is crucial to clarify that the concept of "longitudinal recovery of SSC" downstream of a dam does not refer to restoration to SSC before dam

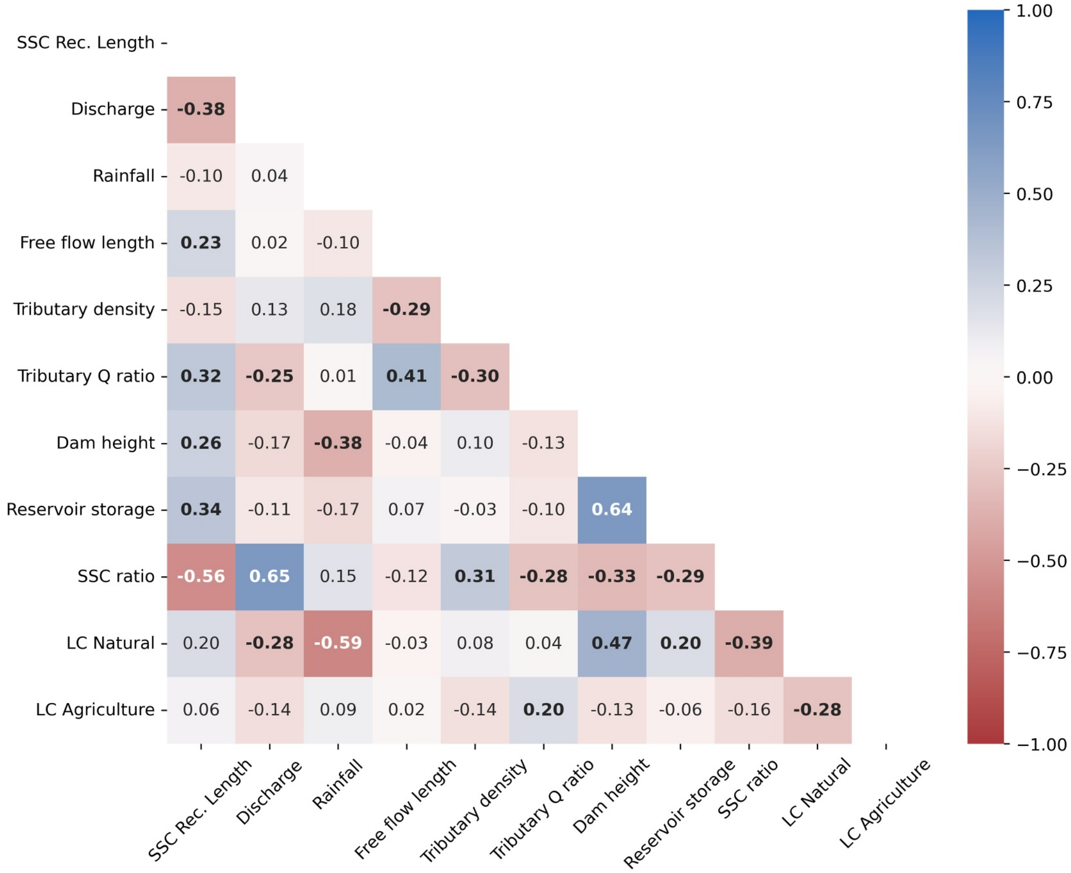

Figure 6. Heatmap showing the simple correlation matrix for longitudinal suspended sediment concentration recovery lengths and potential factors that influence recovery length. Blue and red represent positive and negative correlation values respectively. Statistically significant correlation values (alpha value 0.05) are shown in bold letters.

construction, but rather over space upstream of the reservoir using the long-term mean river SSC in the period after dam construction.

Unrecovered rivers could be in a chronic sediment deficit state, which might cause bank erosion. Dam-related sediment deficit coupled with river channelization by levees might cause substantial streambed incision (Remo et al., 2009, 2016). The recovery of suspended sediment affects channel migration and geomorphic stability of rivers (Jurotich et al., 2021) which is critical for the protection of infrastructure near rivers. Downstream sediment balance over time and space is desirable to achieve geomorphic stability and rehabilitate river ecosystems (Schmidt & Wilcock, 2008). Our spatially explicit SSC observations provide a new approach to quantify SSC downstream recovery in large rivers. The 40-year Landsat record provides a time-integrated and network scale perspective of SSC changes along rivers.

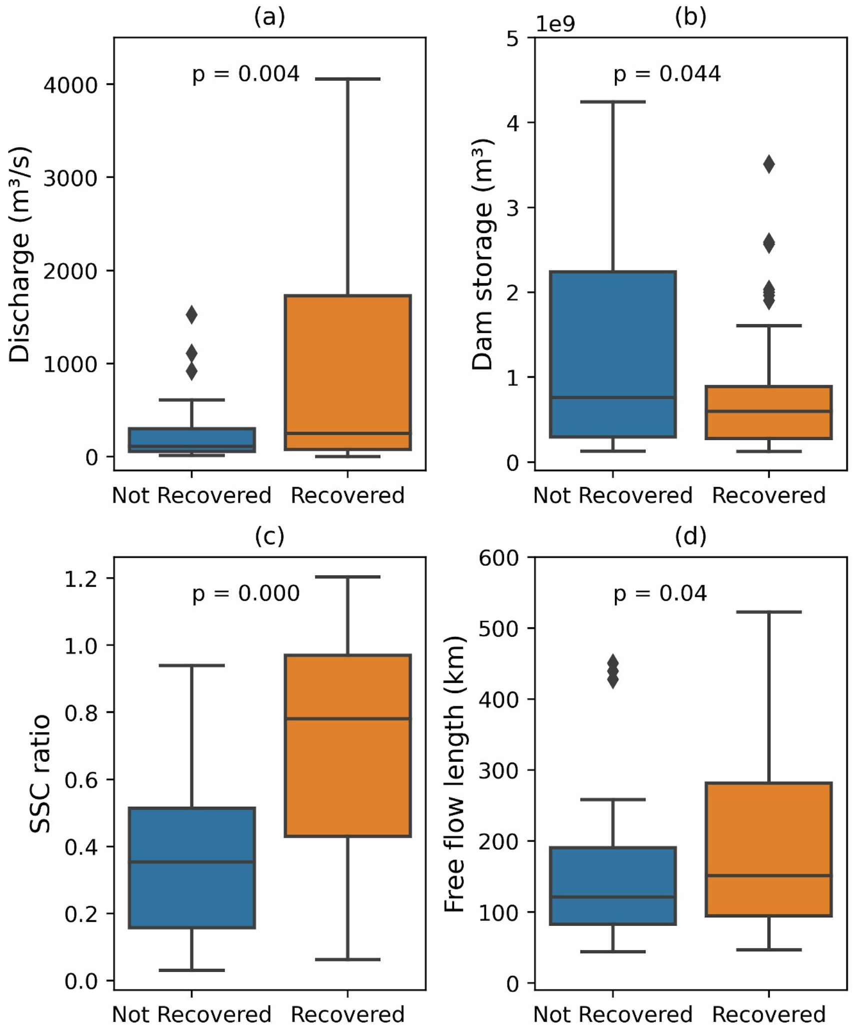

Figure 7. Most important factors associated with suspended sediment concentration (SSC) recovery. Boxplots show factors with significant differences (alpha = 0.05) in (a) Discharge, (b) Dam storage, (c) SSC ratio, and (d) Free flow length in recovered versus non-recovered rivers. The median value is shown as a black line inside the box.

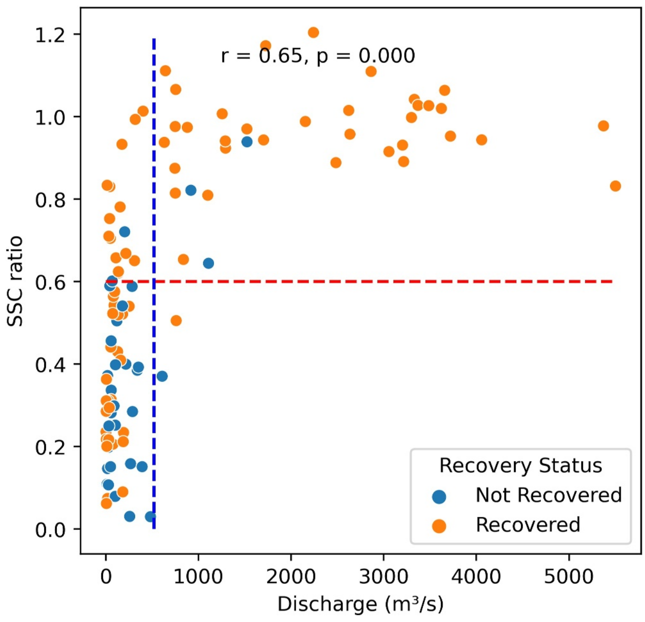

Figure 8. Scatter plots of the suspended sediment concentration (SSC) ratio as a function of river discharge. Orange and blue dots represent dams with SSC recovered and SSC non-recovered dams respectively. There was a statistically significant correlation (alpha = 0.05).

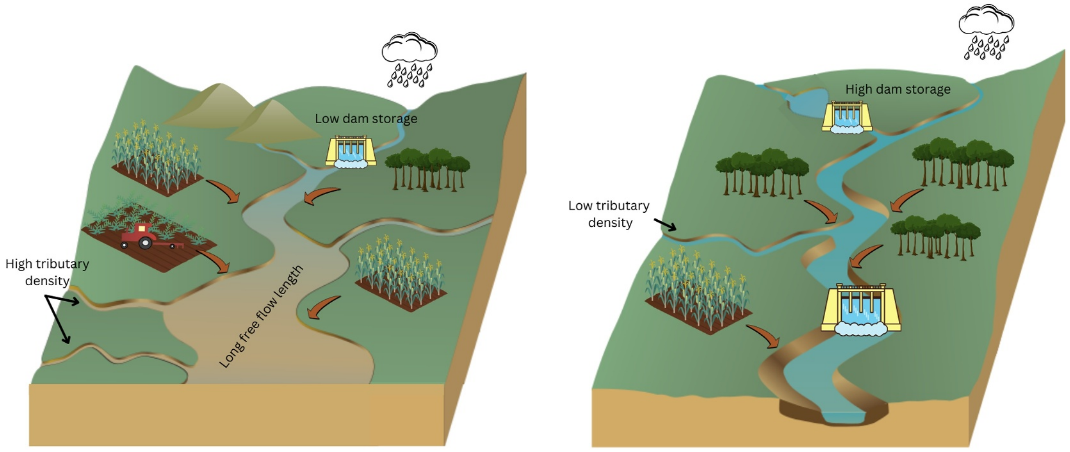

Figure 9. Conceptual diagrams showing factors affecting suspended sediment concentration recovery downstream of the dam in recovered (left) and non-recovered (right) rivers.

Data Availability Statement

Database summary for all dams used in this study is provided here. All data used here are publicly available including:

RivSed (Gardner et al., 2023a, 2023b).

StreamCat (Hill et al., 2016).

NHDplusV2 (Moore & Dewald, 2016a, 2016b).

NABD (Ostroff et al., 2013).

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References

Best, J. (2019). Anthropogenic stresses on the world's big rivers. *Nature Geoscience*, *12*(1), 7–21. https://doi.org/10.1038/s41561-018-0262-x

Beveridge, C., Hossain, F., & Bonnema, M. (2020). Estimating impacts of dam development and landscape changes on suspended sediment concentrations in the Mekong River Basin's 3S tributaries. *Journal of Hydrologic Engineering*, *25*(7), 05020014. https://doi.org/10.1061/(asce)he.1943-5584.0001949

Brandt, S. A. (2000a). Classification of geomorphological effects downstream of dams. *Catena*, *40*(4), 375–401. https://doi.org/10.1016/s0341-8162(00)00093-x

Brandt, S. A. (2000b). Prediction of downstream geomorphological changes after dam construction: A stream power approach. *International Journal of Water Resources Development*, *16*(3), 343–367. https://doi.org/10.1080/713672510

Brune, G. M. (1953). Trap efficiency of reservoirs. *Eos, Transactions American Geophysical Union*, *34*(3), 407–418.

Cohen, S., Syvitski, J., Ashley, T., Fekete, B., & Lammers, R. (2021). Trends and drivers of bedload and suspended sediment fluxes in global rivers. In *AGU fall meeting abstracts* (Vol. 2021, pp. EP55F–1165).

Dethier, E. N., Renshaw, C. E., & Magilligan, F. J. (2022). Rapid changes to global river suspended sediment flux by humans. *Science*, *376*(6600), 1447–1452. https://doi.org/10.1126/science.abn7980

Gardner, J., Pavelsky, T. M., Topp, S., Yang, X., & Ross, M. R. (2023b). River sediment database (RivSed) (v1.1) [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.7938267

Gardner, J., Pavelsky, T. M., Topp, S., Yang, X., Ross, M. R., & Cohen, S. (2023a). Human activities change suspended sediment concentration along rivers. *Environmental Research Letters*, *18*(6), 064032. https://doi.org/10.1088/1748-9326/acd8d8

Gholizadeh, M. H., Melesse, A. M., & Reddi, L. (2016). A comprehensive review on water quality parameters estimation using remote sensing techniques. *Sensors*, *16*(8), 1298. https://doi.org/10.3390/s16081298

Ghosh, K. G. (2022). Sediment transport at the river confluences: Few observations from a sub-tropical plateau fringe river of eastern India. *Geology, Ecology, and Landscapes*, *6*(2), 75–98. https://doi.org/10.1080/24749508.2020.1752501

Graf, W. L. (2006). Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology*, *79*(3–4), 336–360. https://doi.org/10.1016/j.geomorph.2006.06.022

Grant, G. E., Schmidt, J. C., & Lewis, S. L. (2003). A geological framework for interpreting downstream effects of dams on rivers. *Water Science and Application*, *7*, 209–225.

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., et al. (2019). Mapping the world's free-flowing rivers. *Nature*, *569*(7755), 215–221. https://doi.org/10.1038/s41586-019-1111-9

Hill, R. A., Weber, M. H., Leibowitz, S. G., Olsen, A. R., & Thornbrugh, D. J. (2016). The stream-catchment (StreamCat) dataset: A database of watershed metrics for the conterminous United States [Dataset]. *JAWRA Journal of the American Water Resources Association*, *52*(1), 120–128. https://doi.org/10.1111/1752-1688.12372

Hoffmann, T. O., Baulig, Y., Vollmer, S., Blöthe, J. H., Auerswald, K., & Fiener, P. (2023). Pristine levels of suspended sediment in large German river channels during the Anthropocene? *Earth Surface Dynamics*, *11*(2), 287–303. https://doi.org/10.5194/esurf-11-287-2023

Jacobson, R. B., & Galat, D. L. (2008). Design of a naturalized flow regime—An example from the lower Missouri River, USA. *Ecohydrology: Ecosystems, Land and Water Process Interactions, Ecohydrogeomorphology*, *1*(2), 81–104. https://doi.org/10.1002/eco.9

Jurotich, M., Cardona, N., Vázquez, B., Wetzel, R., Cowman, T., & Sweeney, M. (2021). Contributions of suspended load from Missouri River tributaries, southeast South Dakota, and northeast Nebraska: Building a sediment budget. *River Research and Applications*, *37*(4), 511–521. https://doi.org/10.1002/rra.3767

Kondolf, G. M. (1997). Hungry water: Effects of dams and gravel mining on river channels. *Environmental Management*, *21*(4), 533–551. https://doi.org/10.1007/s002679900048

Kotzé, P. (2022). *The world's dams: Doing major harm but a manageable problem?* Mongabay.

Lee Rodgers, J., & Nicewander, W. A. (1988). Thirteen ways to look at the correlation coefficient. *The American Statistician*, *42*(1), 59–66. https://doi.org/10.1080/00031305.1988.10475524

Li, H. Y., Tan, Z., Ma, H., Zhu, Z., Abeshu, G. W., Zhu, S., et al. (2022). A new large-scale suspended sediment model and its application over the United States. *Hydrology and Earth System Sciences*, *26*(3), 665–688. https://doi.org/10.5194/hess-26-665-2022

Milliman, J. D., & Farnsworth, K. L. (2013). *River discharge to the coastal ocean: A global synthesis*. Cambridge University Press.

Moore, R. B., & Dewald, T. G. (2016a). The road to NHDPlus—Advancements in digital stream networks and associated catchments. *JAWRA Journal of the American Water Resources Association*, *52*(4), 890–900. https://doi.org/10.1111/1752-1688.12389

Moore, R. B., & Dewald, T. G. (2016b). The road to NHDPlus—Advancements in digital stream networks and associated catchments [Dataset]. *JAWRA Journal of the American Water Resources Association*, *52*(4), 890–900. https://doi.org/10.1111/1752-1688.12389

Moragoda, N., Cohen, S., Gardner, J., Muñoz, D., Narayanan, A., Moftakhari, H., & Pavelsky, T. M. (2023). Modeling and analysis of sediment trapping efficiency of large dams using remote sensing. *Water Resources Research*, *59*(6), e2022WR033296. https://doi.org/10.1029/2022wr033296

Narayanan, A., Cohen, S., & Gardner, J. R. (2023). Riverine sediment response to deforestation in the Amazon Basin. *EGUsphere*, *2023*, 1–27.

Nienhuis, J. H., Ashton, A. D., Edmonds, D. A., Hoitink, A. J. F., Kettner, A. J., Rowland, J. C., & Törnqvist, T. E. (2020). Global-scale human impact on delta morphology has led to net land area gain. *Nature*, *577*(7791), 514–518. https://doi.org/10.1038/s41586-019-1905-9

Nigatu, A. (2014). *Impact of land use land cover change on soil erosion risk: The case of Denki River catchment of Ankober Woreda*. Addis Ababa University.

Ostroff, A., Wieferich, D., Cooper, A., & Infante, D., & USGS Aquatic GAP Program. (2013, 2012). National anthropogenic barrier dataset (NABD) [Dataset]. *U.S. Geological Survey—Aquatic GAP Program*. Retrieved from https://www.sciencebase.gov/catalog/item/56a7f9dce4b0b28f1184dabd

Pavelsky, T. M., & Smith, L. C. (2009). Remote sensing of suspended sediment concentration, flow velocity, and lake recharge in the Peace-Athabasca Delta, Canada. *Water Resources Research*, *45*(11), W11417. https://doi.org/10.1029/2008wr007424

Petts, G. E. (1979). Complex response of river channel morphology subsequent to reservoir construction. *Progress in Physical Geography*, *3*(3), 329–362. https://doi.org/10.1177/030913337900300302

Phillips, J. D. (2010). The job of the river. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, *35*(3), 305–313. https://doi.org/10.1002/esp.1915

Pyron, M., & Neumann, K. (2008). Hydrologic alterations in the Wabash River watershed, USA. *River Research and Applications*, *24*(8), 1175–1184. https://doi.org/10.1002/rra.1155

Remo, J. W., Heine, R. A., & Ickes, B. S. (2016). Particle size distribution of main-channel-bed sediments along the upper Mississippi River, USA. *Geomorphology*, *264*, 118–131. https://doi.org/10.1016/j.geomorph.2016.04.012

Remo, J. W., Pinter, N., & Heine, R. (2009). The use of retro-and scenario-modeling to assess effects of 100+ years river of engineering and land-cover change on Middle and Lower Mississippi River flood stages. *Journal of Hydrology*, *376*(3–4), 403–416. https://doi.org/10.1016/j.jhydrol.2009.07.049

Renwick, W. H., Smith, S. V., Bartley, J. D., & Buddemeier, R. W. (2005). The role of impoundments in the sediment budget of the conterminous United States. *Geomorphology*, *71*(1–2), 99–111. https://doi.org/10.1016/j.geomorph.2004.01.010

Rice, S. P., & Church, M. (2001). Longitudinal profiles in simple alluvial systems. *Water Resources Research*, *37*(2), 417–426. https://doi.org/10.1029/2000wr900266

Ritchie, J. C., Cooper, C. M., & Yongqing, J. (1987). Using Landsat multispectral scanner data to estimate suspended sediments in Moon Lake, Mississippi. *Remote Sensing of Environment*, *23*(1), 65–81. https://doi.org/10.1016/0034-4257(87)90071-x

Ross, M. R., Topp, S. N., Appling, A. P., Yang, X., Kuhn, C., Butman, D., et al. (2019). AquaSat: A data set to enable remote sensing of water quality for inland waters. *Water Resources Research*, *55*(11), 10012–10025. https://doi.org/10.1029/2019wr024883

Sadeghi, S. H., & Singh, V. P. (2017). Dynamics of suspended sediment concentration, flow discharge and sediment particle size interdependency to identify sediment source. *Journal of Hydrology*, *554*, 100–110. https://doi.org/10.1016/j.jhydrol.2017.09.006

Schmidt, J. C., & Wilcock, P. R. (2008). Metrics for assessing the downstream effects of dams. *Water Resources Research*, *44*(4), W04404. https://doi.org/10.1029/2006wr005092

Seegers, B. N., Stumpf, R. P., Schaeffer, B. A., Loftin, K. A., & Werdell, P. J. (2018). Performance metrics for the assessment of satellite data products: An ocean color case study. *Optics Express*, *26*(6), 7404–7422. https://doi.org/10.1364/oe.26.007404

Syvitski, J. P., Vorosmarty, C. J., Kettner, A. J., & Green, P. (2005). Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science*, *308*(5720), 376–380. https://doi.org/10.1126/science.1109454

Tadesse, L., Suryabhagavan, K. V., Sridhar, G., & Legesse, G. (2017). Land use and land cover changes and Soil erosion in Yezat Watershed, North Western Ethiopia. *International Soil and Water Conservation Research*, *5*(2), 85–94. https://doi.org/10.1016/j.iswcr.2017.05.004

Vörösmarty, C. J., Meybeck, M., Fekete, B., & Sharma, K. (1997). *The potential impact of neo-Castorization on sediment transport by the global network of rivers* (Vol. 246, pp. 261–273). IAHS Publication.

Vörösmarty, C. J., Meybeck, M., Fekete, B., Sharma, K., Green, P., & Syvitski, J. P. (2003). Anthropogenic sediment retention: Major global impact from registered river impoundments. *Global and Planetary Change*, *39*(1–2), 169–190. https://doi.org/10.1016/s0921-8181(03)00023-7

Walling, D. E., & Webb, B. W. (1986). Solutes in river systems. In S. T. Trudgill (Ed.), *In solute process* (pp. 251–320). Wiley.

Williams, G. P., & Wolman, M. G. (1984). *Downstream effects of dams on alluvial rivers* (p. 61). Geological Survey Professional Paper 1286. USGS.

Yepez, S., Laraque, A., Martinez, J. M., De Sa, J., Carrera, J. M., Castellanos, B., et al. (2018). Retrieval of suspended sediment concentrations using Landsat-8 OLI satellite images in the Orinoco River (Venezuela). *Comptes Rendus Geoscience*, *350*(1–2), 20–30. https://doi.org/10.1016/j.crte.2017.08.004

Zhang, M., Dong, Q., Cui, T., Xue, C., & Zhang, S. (2014). Suspended sediment monitoring and assessment for Yellow River estuary from Landsat TM and ETM+ imagery. *Remote Sensing of Environment*, *146*, 136–147. https://doi.org/10.1016/j.rse.2013.09.033